MATERIALS CHANGES TAKING PLACE DURING THE OPENING OF EXPLODING FOIL SWITCHES

Charles Stein
Air Force Weapons Laboratory
Kirtland Air Force Base
Albuquerque, New Mexico 87117

Summary

Exploding foil switches used to couple very large amounts of stored energy to impulsively driven loads seem to attain a limit in the rapidity at which they open. A materials science analyses of the changes which take place during the opening of copper and aluminum foil fuses, which use 100 μm glass beads as the quenching medium was conducted. A suggested sequence of events which takes place in SHIVA opening switches which interrupt current from 45 KJ of stored energy during the 200 n seconds required to open these switches, is proposed.

Introduction

The performance of inductive pulse compression systems as drivers for energetic plasma implosions is predicated, in part, on the operational characteristics of the opening switch. This switch must be capable of interrupting currents and voltages in the mega range while opening in less than two hundred nanoseconds. The Air Force Weapons Laboratory has successfully used exploding "fuses" as opening switches in their SHIVA program where 1.9MJ of stored energy has been coupled to a 12 mΩ, 5.8 nH load in 190 ns generating 300 kV across the load at 7.5 MA.

Figure 1 shows a schematic representation of the fuse assembly [1] which consists of a single fold of either 0.001-in aluminum or copper foil surrounded by 100 μm glass beads which act as a quenching medium. Shock is absorbed by 1 in of medium density polyurethane foam on either side of the foil/bead assembly.

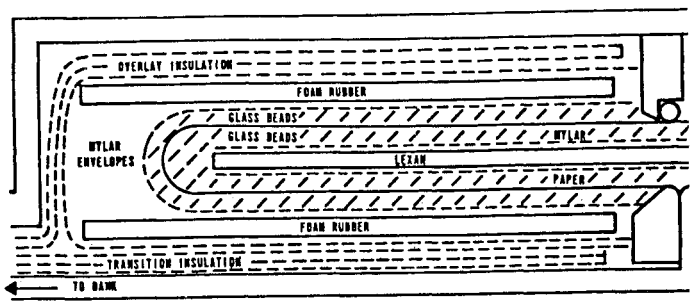

Fig 1. Schematic arrangement of opening switch (From Reference (1).

Repeated use of these switches has indicated that there may be some limit to the rapidity at which they open. In order to understand what materials and geometric arrangements may limit the attainment of faster switch opening times, a materials science post-mortem analyses of the changes which take during the operation of foil fuses was conducted on aluminum and copper switches. These switches were used to couple 45 kJ of stored energy to dummy loads.

In this study, scanning electron microscopy (SEM), Auger analyses, electron spectroscopy for chemical analyses (ESCA), x-ray diffraction, transmission electron microscopy (TEM) and electron diffraction techniques were used to study material changes taking place in foil switches. Results using each of these procedures are discussed sequentially below.

Copper Foil Switch

Scanning Electron Microscopy

Low magnification SEM pictures and corresponding x-ray fluorescent chemical analyses showed that the quenching medium used in the AFWL exploding foil switches consists of soda-lime-glass spheres of relatively uniform 100 μm diameters. After use in a 45 kJ system the glass spheres have fused together over a width of about 500 μm on either side of the previous position of the copper foil, which has vaporized. See Fig 2. The compressive pulse of the

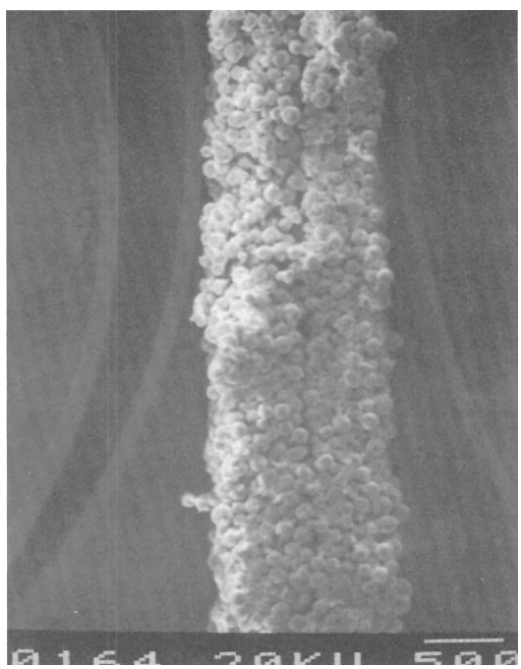

Figure 2. Scanning Electron Micrograph of copper/glass switch. Marker indicates 500 μm.

shock wave which is generated by the exploding foil compressed many of the softened spheres together while the subsequent rarefraction wave pulled them apart producing drawn out necks between ajacent

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14. ABSTRACT

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spheres. See Figure 3.

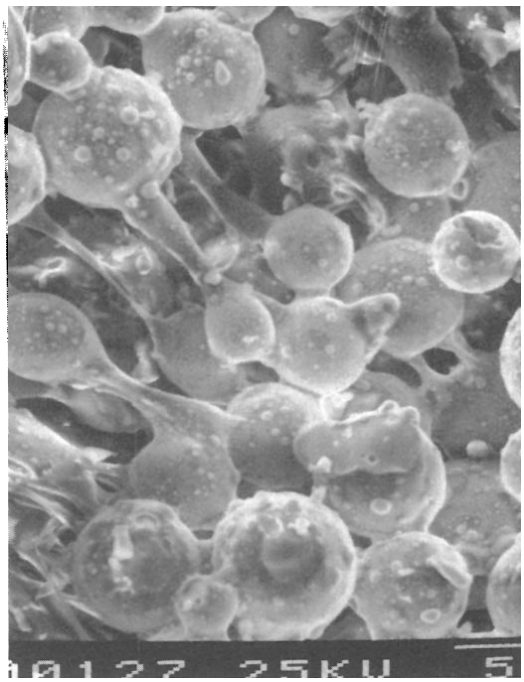

Figure 3. Scanning Electron Micrograph of copper/glass switch showing necks formed between glass spheres due to rarefraction wave. Marker indicates 50 μm.

In general, all of the 100 μm glass spheres are covered on all sides with smaller glass beads and glass fragments which must have resulted from a great many of them ricocheting off of ajacent spheres. See Figure 4. X-ray fluorescent chemical analyses shows

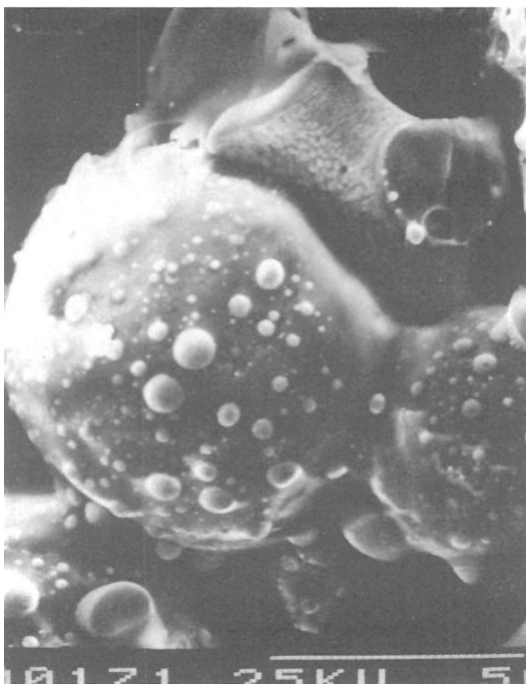

Figure 4. Scanning Electron Micrograph of copper/glass switch showing smaller droplets and neck between glass spheres. Marker indicates 50 μm.

that these small beads, many less than 0.5 μm, as well as the 100 μm spheres and the necks which form between them are covered with a layer of copper (and mixed copper oxides). For the most part, the 100 μm glass spheres did not show evidence of spall fracture due to the passage of the shock wave. Close examination of the surface of some of the smaller beads nearest the prior position of the copper foil, at high magnification in the SEM, indicated that subsequent re-evaporation of both copper as well as glass may have taken place. Note, in Figure 4 the self-made craters on the surface of the 100 μm spheres in which the smaller copper coated glass beads reside. The upper portion of Figure 4 shows a neck which formed between two 100 μm glass spheres, both of which have subsequently broken off. Small nuclei of copper oxide coated copper desposits are clearly shown on the surface of the neck, while the fracture surface is devoid of these deposits. This implies that the small glass droplets as well as the copper which coated these surfaces arrived after the rarefraction had passed through this cross section and formed the neck between the 100 μm spheres.

Auger, ESCA and X-ray Analyses

Auger and ESCA analyses were conducted on copper-foil - glass quenching opening switch samples used in a 45 kJ storage system. Analyses from surfaces at positions nearest to the prior location of the .001 in copper foil showed that sodium, calcium as well as copper were present, in addition to silicon and oxygen from the glass spheres. In addition, ESCA analyses indicated the possible presence of a CuO line which was later carroberated by x-ray as well as electron diffraction spectra.

Transmission Electron Microscopy

Transmission electron microscopy samples were prepared from different positions in the cross-section of the fused copper foil - glass bead opening switches. Clusters of beads were broken away from the cross-section of interest under distilled water and scooped up on collodian films which were supported by copper grids. Figure 5 was taken with a Joel 100B transmission electron microscopy operating

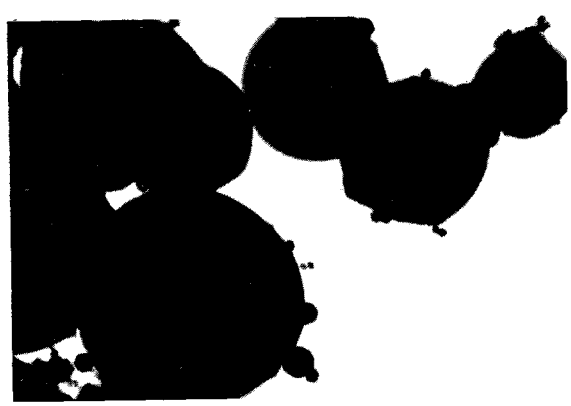

Figure 5. Transmission Electron Micrograph of copper/glass switch showing growth of single crystals of copper on glass bead surfaces.

at 100 kV and shows a typical cluster of glass beads at an original magnification of 13,000 X. The beads

range in diameter from 2.5 μm to 4 μm and show smaller, single cyrstals of copper growing out from their surfaces. These single crystal are surrounded by a thin film of copper oxide (light, transparent areas) which are predoninantly Cu_2O. The electron

diffraction pattern showed copper and copper oxide single crystal diffraction spots. Since the size of these glass beads are so much smaller than the starting size of 100 μm, it must be presumed that they were molten droplets produced by the hot copper foil exploding against the first column of glass spheres. These single crystals, which grew with an oxide diffusion barrier surrounding them, must be considered to have formed slowly. This implies that the switch opening time is long, since copper vapor is still available from the plasma to support single crystal growth.

Aluminum Foil Switches

Scanning Electron Microscopy

The cross section morphology of the aluminum foil-glass sphere opening switches used in the 45 KJ storage system differed from that of the copper foil switches. In the aluminum switch those glass spheres nearest to the prior position of the aluminum foil which remained after the foil had vaporized were conspicuously smooth and devoid of both glass fragments and small beads. See Figure 6 in which the

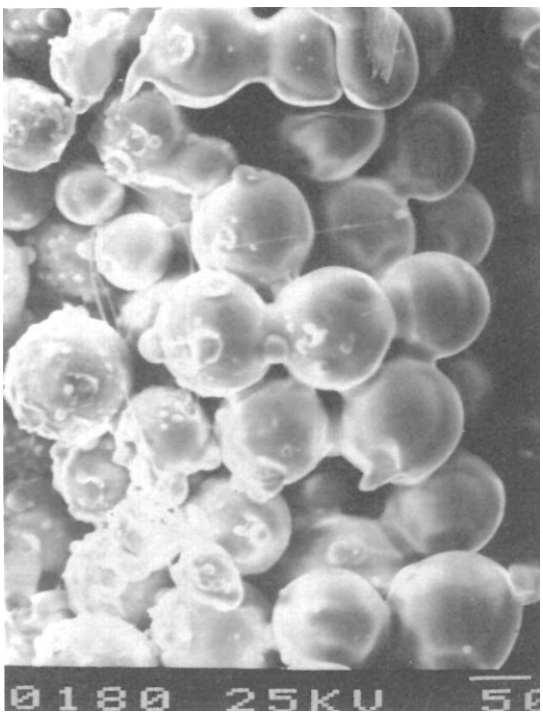

Figure 6. Scanning Electron Micrograph of aluminum/glass switch showing smooth glass spheres nearest prior aluminum foil position, which was on the extreme right.

prior position of the aluminum foil was on the extreme right. Auger analyses showed that the surfaces of these glass spheres were depleated of both sodium and calcium. This suggests that they remained hot enough and long enough to re-evaporate molten fragments as well as the loosely bonded sodium and calcium glass constituents off their surfaces. Like the copper foil switches, compressed spheres and necks were formed between glass spheres. See the upper portion of Fig 6. In addition, craters and glass filaments were in evidence, due to the ricochetting of molten glass at positions in the fused cross-section away from the original site of the foil. All of these latter surfaces were covered with aluminum.

Auger Analyses

Chemical analyses at depths below the surfaces of those glass beads which were nearest to the prior position of the aluminum foil were carried out by Auger techniques. These surfaces were covered with aluminum but were depleated in both sodium and calcium and required a total sputtering time of 35 minutes before these glass constituents were again in evidence. This suggests that sodium and calcium ions are present in the plasma produced by the exploding aluminum foil and may be contributing to its late time conductivity. Since the aluminum, which covered the glass spheres, apperas on the surfaces which have been depleated of sodium and calcium, it must be presumed that the latter constituents evaporated from the glass during its heating up but prior to the explosion of the aluminum foil.

Transmission Electron Microscopy

Aluminum-glass sphere samples were prepared for transmission electron microscopy in a manner similar to that used for the copper switch samples. In a variation of this technique, ultrasonic vibration in distilled water, was used to separate the small glass bead clusters from the larger glass spheres. Single crystals of aluminum were seen on the surfaces of the small beads which had deposited on the larger 100 μm glass spheres. The morphology of growth of these single crystals, which were surrounded by an oxide film, was found to be similar to that of the single crystal copper growth. Analyses of the electron diffraction patterns accompanying the transmission images indicated that the oxides are either δ or K aluminum oxide. See Figure 7. Occasionally, the

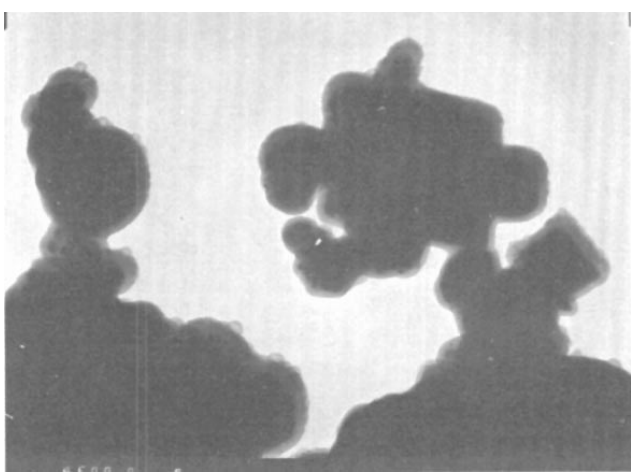

Figure 7. Transmission Electron Micrograph of aluminum/glass switch showing growth of single crystals of aluminum surrounded by an oxide film. Original magnification was 20,000 X.

unusual surface configuration shown in Figure 8 appeared. Selected area electron diffraction

patterns from these surfaces indicated that the fine fila are probably silica which has deposited on a layer of single crystal aluminum which is, in turn, supported by small glass bead substrates. Heating of these fila by the electron beam in the microscope caused them to agglomerate into smooth "fingers" which can be seen in Figure 8 at the base of the fine fila.

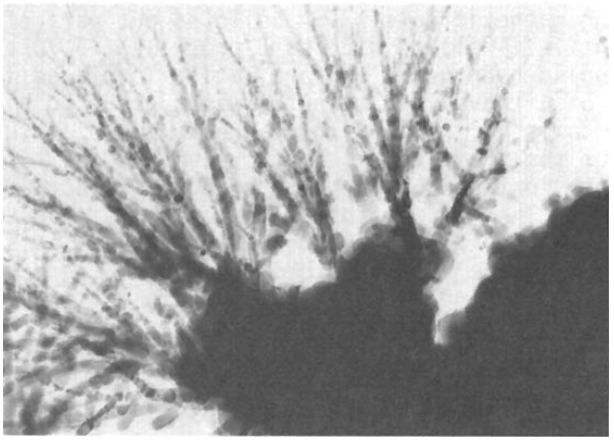

Figure 8. Transmission Electron Micrograph of aluminum/glass switch showing growth of fine silica fila on aluminum single crystal which was deposited on small glass droplets. Original magnification was 60,000 X.

Conclusions and Recommendations

1. The glass spheres used as a quenching medium in both the copper and aluminum foil switches, soften, melt and probably break up into fine droplets prior to the vaporization of these foils.

2. The sudden vaporization of the metallic foils produces a shock wave whose compressive pulse flattens the glass spheres against each other while the subsequent rarefraction wave produces necks between the spheres.

3. Metallic vapor from the plasma deposits on these necks as well as on the smaller glass beads and other glass fragments.

4. Single crystals of copper, surrounded by a thin oxide film, grow on the surfaces of the small glass beads, thereby further depleating the plasma of vaporized copper.

5. In the case of the aluminum switch, re-evaporation of the shock produced glass debris off of the glass spheres nearest to the prior foil position takes place. In addition, the surfaces of these spheres become depleated in both sodium and calcium. Subsequently, aluminum vapor from the still hot plasma is deposited on the smooth surfaces of the depleated glass spheres.

6. Late time quenching of the metallic plasma is suggested by: a) Step 3, since the passage of both a compressive as well as a rarefraction wave through a porous material (loose packing of glass spheres) prior to the deposition of a metallic coating on the necks which are formed is a time consuming process; b) step 4, the growth of copper as well as aluminum through an oxide layer, even though the temperature may be quite high, is another slow process and c) step 5, in which silica growth takes place indicates late time plasma quenching since the silica forming the fila is still being provided by tha plasma which must also contain conductive sodium and calcium ions.

7. The use of higher melting quenching media, such as silica or alumina beads, is suggested.

8. The rarefraction wave might be used to speed the opening of these switches by juditiously choosing the thickness of the quenching media and replacing the foam rubber shock absorber by a hard insulator so that the rebounding rarefraction waves will arrive at the position of the conducting plasma in a timely manner and disperse it.

9. The selected area diffraction pattern corresponding to the transmission electron micrograph of the single crystals of aluminum shown in Fig 7 contain aluminum oxide spots. The spot patterns have been indexed and can be identified as either δ or K aluminum oxide. δ aluminum oxide is normally stable above 750°C and transforms to θ alumina at 1000°C.

According to Lippens and de Boer[2], however, the presence of sodium ions from a small quantity of Na_2O

will inhibit the formation of δ Alumina even at temperatures near 950°C. Since δ alumina has tentatively been identified as growing on the single crystals of aluminum which appear on the surface of the small glass droplets and since sodium ions are assumed to be present in the plasma during opening of the switch, it can be postulated that the oxide growth is taking place at temperatures in excess of 950°C. Only a limited number of selected area diffraction patterns have been obtained from these single crystals. Consequently, a more definitive determination of the diffraction pattern and the corresponding crystal structure of the aluminum oxide remain to be accomplished.

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Reference

(1) "Inductive Store Pulse Compression System for Driving High Speed Plasma Implosions," R.E. Reinovsky, et al; IEEE Transactions on Plasma Science, Vol. PS-10, No. 2, June 1982

(2) B.C. Lippens and J.H. deBoer, "Study of Phase Transformations during Calcination of Aluminum Hydroxides by selected Area Electron Diffraction", Acta Crystalography, V.17, p. 1312, 1964.